In Situ and Remote Monitoring of Water Quality in South Puget Sound: The ORCA Time-Series

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[Editor's note: Figures for Reuf et al appear at the end of the paper.]

Abstract
We obtained high frequency measurements of chemical, physical, and biological properties throughout the water column at a fixed station using an autonomous moored profiling system in south Puget Sound, a largely undeveloped area subject to extensive future urbanization and potentially sensitive to impacts from eutrophication. Measurements were taken every two to six hours for over two years using surface meteorological sensors and a profiling underwater instrument package consisting of a Seabird CTD, dissolved oxygen electrode, Wetlabs transmissometer and chlorophyll fluorometer.

The data set reveals strong seasonal forcing in surface temperature and salinity, producing frequent intermittent periods of either strong stratification or deep mixing throughout the summer. Oxygen saturation varied from under-saturation (~60%) at all depths during the winter, to mid-summer values near saturation (~90-100%) at depth and supersaturated (~150%) at the surface. Chlorophyll and oxygen co-varied, with the chlorophyll maximum moving subsurface after the spring bloom. A box model using the data set to estimate net biological oxygen production gave values of net community carbon production that were significantly lower than the carbon fixation determined by ^{14}C incubation measurements.

Introduction
We obtained high frequency measurements of chemical, physical, and biological properties throughout the water column at a fixed station in Carr Inlet, Puget Sound (Figure 1) using the Oceanic Remote Chemical Analyzer (ORCA), an autonomous moored profiling system (Figure 2; Dunne et al. 2002). We define south Puget Sound as the most inland reaches of the Puget Sound estuary network south of the Tacoma Narrows, an area that is characterized by relatively sluggish circulation, seasonal stratification, and intense phytoplankton blooms coupled with nutrient depletions in the spring and summer months. With extensive urbanization of the area predicted for the next 10 years, south Puget Sound is potentially at risk from the impacts of eutrophication. Measurements were taken every 2 to 6 hours over a 3-year period using surface meteorological sensors and a profiling underwater instrument package consisting of a Seabird CTD, dissolved oxygen electrode, Wetlabs transmissometer and chlorophyll fluorometer. These measurements have provided us with a high resolution, long-term time series of data at one location, enabling us to investigate tidal, diel, seasonal, and inter-annual cycles and trends in stratification, oxygen, water clarity and phytoplankton abundance and community distribution.

Since its deployment in May 2000, ORCA has provided a near-continual stream of high-resolution water quality data from Carr Inlet, with some data gaps due to routine maintenance and malfunctioning instrumentation (2002 results are presented in Figure 3). We are continually conducting data quality assurance, data reduction and time-series analysis in an effort to understand the sources of variability in this ever-growing data set. Throughout the 3 years of data collection, we observed a considerable co-variation in all parameters, indicating a tight coupling between physical and biological processes in Carr Inlet. Throughout the summer and early fall, variability in wind, rainfall and sunlight, forced temperature and salinity between intermittent periods of either strong stratification or deep mixing. The seasonal cycle in temperature and salinity was also intense, with the intermittently high surface temperatures disappearing entirely in the fall and salinity increasing steadily throughout the summer and fall. Oxygen and chlorophyll co-varied in the summer through a combination of physical response to the intermittent stratification and mixing and biological response to primary production and respiration. At depth, we observed the generation and strengthening of low oxygen conditions throughout the summer with destruction of this stratification during the onset of intense mixing in the fall. Oxygen saturation varied from under-saturation (~60%) at all depths during the winter, to mid-summer values near saturation (~90-100%) at depth and supersaturated (~150%) at the surface. A detailed discussion and analysis of the ORCA data is found in Dunne et al. (2002).

2002 Data Analysis

With the 2002 dataset we were able to determine the diurnal oxygen concentration changes by calculating the mean diurnal change measured in over 600 profiles for the period between May 1 and September 30, 2002 (Figure 4). To demonstrate how often one would have to sample to resolve this diurnal oxygen change we randomly sub-sampled the entire 2002 data set at various frequencies. This result (Figure 5) demonstrates that the character of the diurnal oxygen change is lost if samples are done less frequently than every other day.

A one-dimensional oxygen mass balance, in which the oxygen change over time (dO_2/dt) was determined by balancing vertical diffusion, gas exchange with the atmosphere, and net oxygen production (gross oxygen production minus euphotic zone community respiration), was applied to the 2002 dataset to determine a net community oxygen production of 10 mmoles $m^{-2}d^{-1}$. (Relationships derived from the literature were used to calculate gas exchange (Liss and Merlivat 1986) and vertical diffusion (Denman and Gargett 1983) from the observed gradients.) Converting this into carbon using a ΔO_2: ΔC ratio of 1.0 results in a net community production rate of 120 mg C $m^{-2}d^{-1}$. We also estimated gross oxygen production from the observed diurnal oxygen change (Figure 4). Respiration rate was estimated from the nighttime decrease in oxygen, and it was assumed that respiration was constant over the 24-hour period. We further assumed a daily oxygen change of zero (Figure 4). Thus, we calculated the gross oxygen production as the amount of oxygen required to balance the daily respiration, plus the increase observed during the light period of the day. This gave a value of 140 mmoles O_2 $m^{-2}d^{-1}$, which, when combined with the oxygen loss due to gas exchange, 12 mmoles O_2 $m^{-2}d^{-1}$, resulted in a gross oxygen production of 152 mmoles O_2 $m^{-2}d^{-1}$, or approximately 1900 mg C $m^{-2}d^{-1}$. The Washington State Department of Ecology (DOE), using ^{14}C incubation measurements, estimated a primary production of 3400 mg C $m^{-2}d^{-1}$, indicating that less than 10% of the net primary production escapes the euphotic zone in summer. However, the DOE estimate is based on a model developed from data collected during a previous year at a different location in the Puget Sound, so it may not be strictly applicable to Carr Inlet. We are in the process of formulating biogeochemical models that may help us to quantitatively distinguish between the biological and physical effects such that we can understand controls on oxygen concentrations in both the surface and deep waters.

Conclusions

The long term high-resolution dataset collected using the ORCA system has revealed features, such as the diurnal oxygen change, that are not apparent in low-frequency sampling, and has allowed a more accurate calculation of model terms, such as the air-water gas transfer term. The oxygen budget calculation that can be accomplished with these terms allows an estimate of C-export to deep waters, which is one of the primary factors affecting dissolved oxygen drawdown in these waters. This type of data and analyses further our ability to predict summer levels of deepwater oxygen, which is an important water quality parameter, as well as further our understanding of the vulnerability of Carr Inlet to hypoxia through eutrophication.

References

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Liss, Peter S. and Liliane Merlivat, 1986. Air-Sea Gas Exchange Rates: Introduction and Synthesis, **In**: P. Buat- Menard (ed.*),The Role of Air-Sea Exchange in Geochemical Cycling*. Reidel Publishing Company, pp. 113-127.

Figures

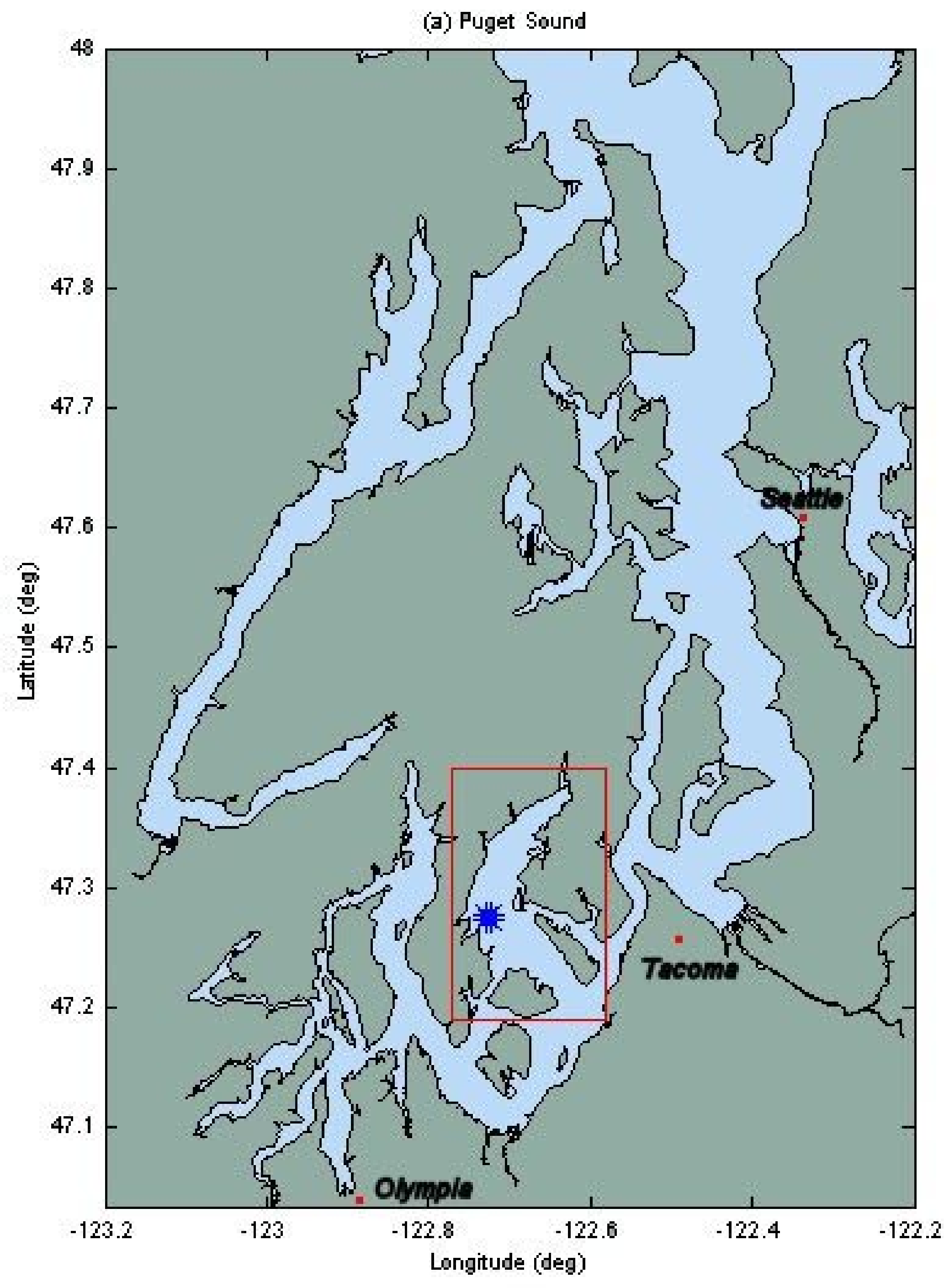

Figure 1. Carr Inlet, Puget Sound, Washington State. Star indicates mooring site.

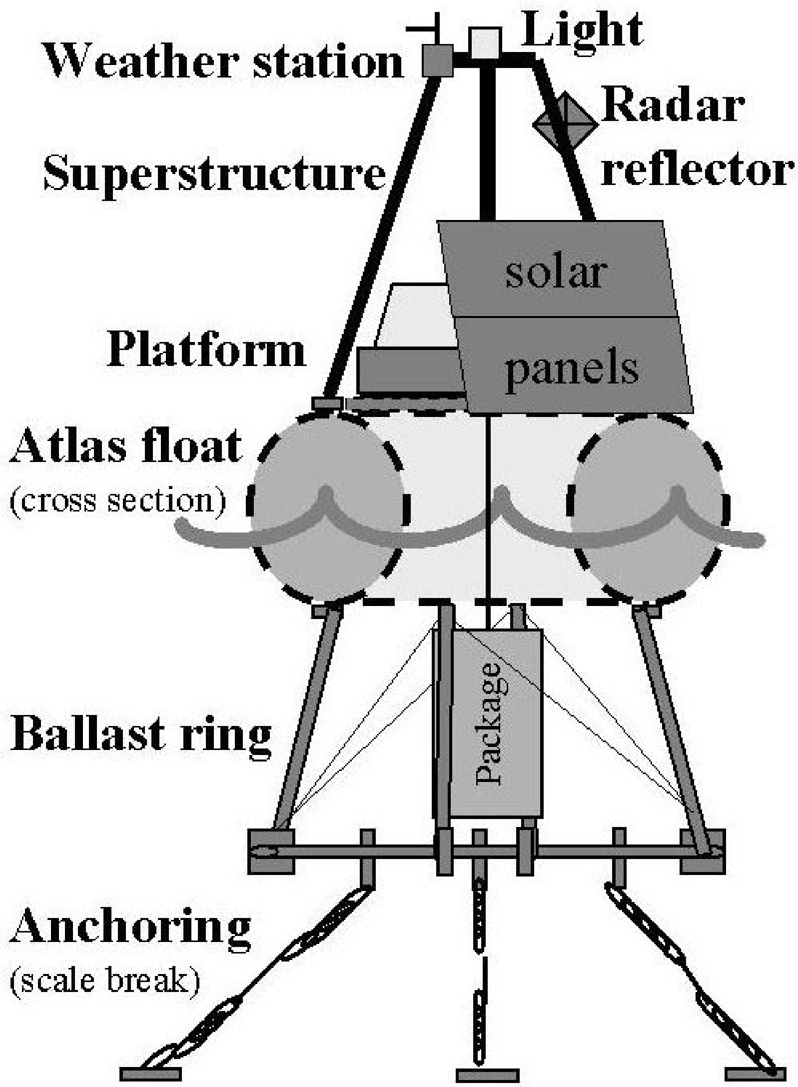

Figure 2: Schematic of the ORCA profiler.

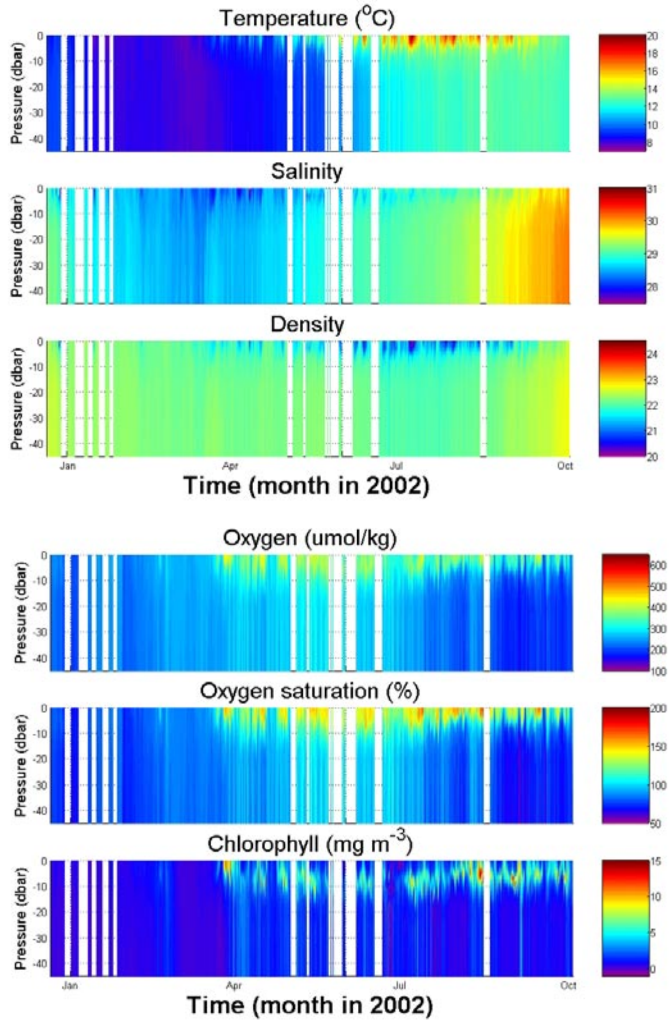

Figure 3. ORCA time-series of temperature, salinity, density, oxygen, oxygen saturation, and chlorophyll fluorescence from January 1, 2002-Dec. 19, 2002

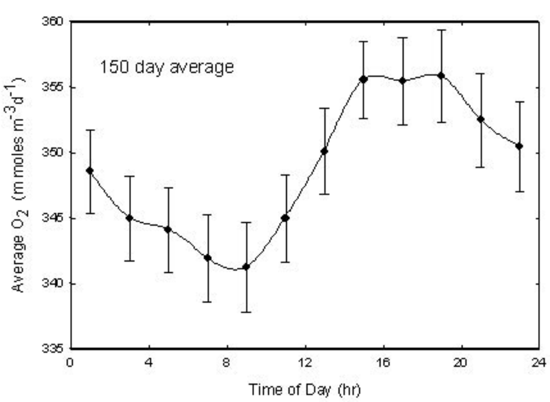

Figure 4. Hourly oxygen averages for all casts from May through September, 2002.

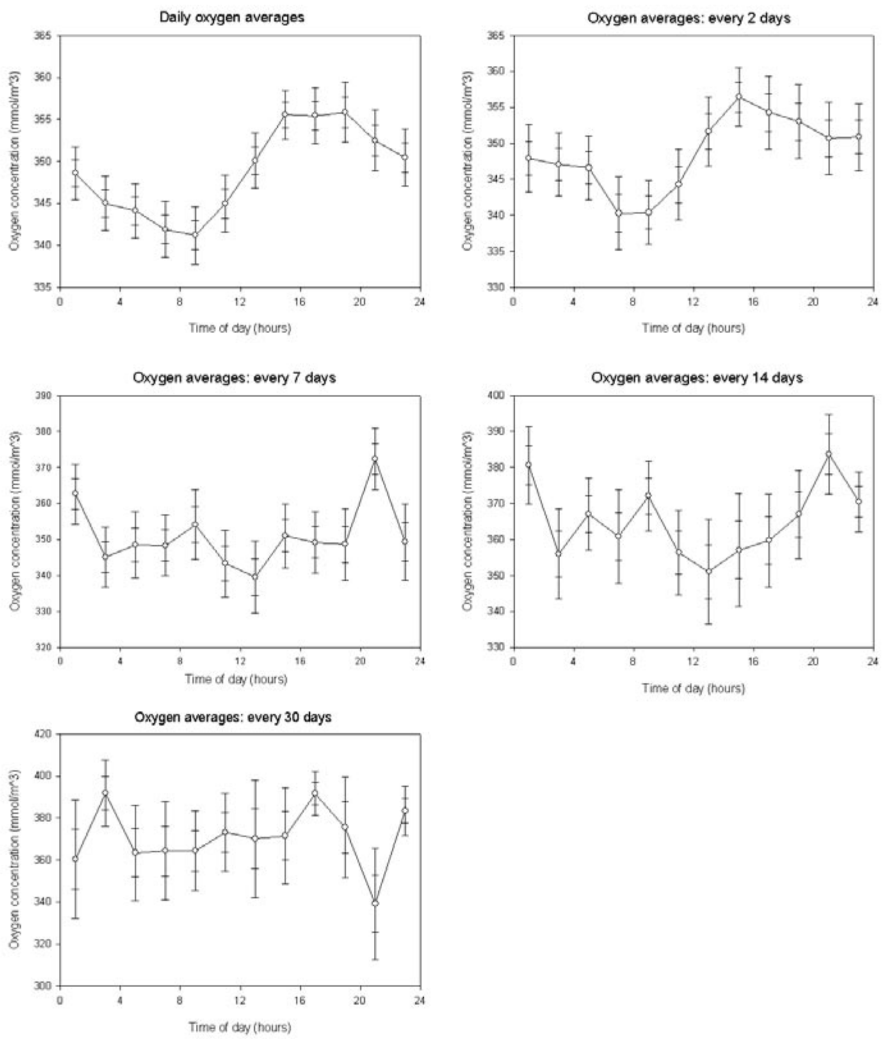

Figure 5. Hourly oxygen averages for all casts from May through September, 2002, using random sampling frequencies.